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THE FUTURE OF CLEAN COMPUTING MAY BE DIRTY

The emergence of the Internet of Things and pervasive sensor networks have generated a surge of research in energy scavenging techniques. We know well that harvesting RF, solar, or kinetic energy enables the creation of battery-free devices that can be used where frequent battery changes or dedicated power lines are impractical. One unusual yet ubiquitous source of power is soil (earth itself) — or more accurately, bacterial communities in soil. Microbial fuel cells (MFCs) are electrochemical cells that harness the activities of microbes that naturally occur in soil, wetlands, and wastewater. MFCs have been a topic of research in environmental engineering and microbiology for decades, but are a relatively new topic in electronics design and research. Most low-power electronics have traditionally opted for batteries, RF energy, or solar cells. This is changing, however, as the limitations and costs of these energy sources hamper our ability to deploy useful systems that last for decades in challenging environments. If large-scale, long-term applications like underground infrastructure monitoring, smart farming, and sensing for conservation are to be possible, we must rethink the energy source.

It is only recently that computational systems have reached low enough operational power where an MFC is feasible as the main power source. This article focuses on soil-based MFCs, also known as terrestrial MFCs or dirt/mud batteries. A future of sensors powered by one of the most common substances on Earth — namely, earth — is tantalizing. Creating a usable MFC-powered system is, of course, not as simple as plugging positive and negative leads into the soil. Nor, it turns out, can we simply attach harvesters designed for other energy sources. This article seeks to familiarize the reader with the promise of MFC-powered electronic devices from the "ground up": we begin with the biochemistry of MFCs, discuss the challenges of harvesting their energy in soils, and consider some of the challenges and potential advantages to building systems powered by MFCs. We close with a discussion on the role MFCs can play in the growing field of eco-friendly electronics.

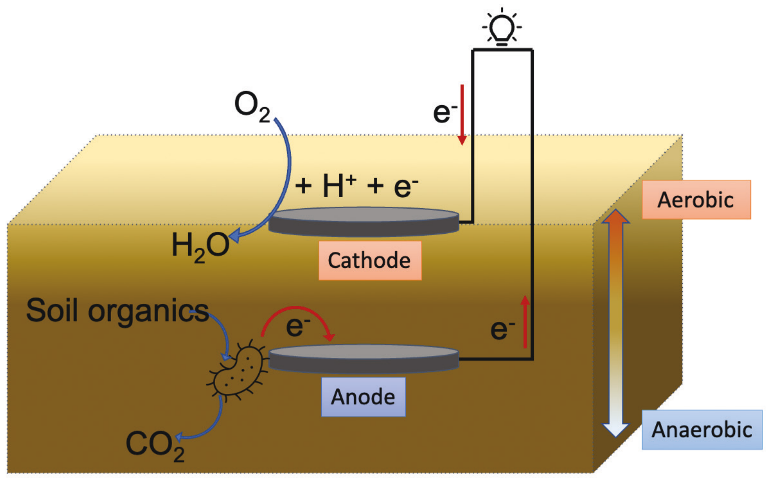

FIGURE 1. Soil microorganisms transform chemical energy to electrical energy in a microbial fuel cell.

THE BIOELECTROCHEMISTRY OF MFCS

So how does one harvest energy from soil? In fact, the energy is actually from specific microorganisms commonly found in soil, termed exoelectrogens [1,2]. At their essence, these microorganisms derive energy for metabolism and growth by catalyzing redox reactions, which by definition involves the transfer of electrons between a donor and an acceptor. An extraordinarily complex community of microorganisms can harvest energy for growth and maintenance from organic matter in the soil, which acts as the electron donor. Among these microorganisms, some bacterial species can transport the electrons generated from soil organic matter oxidation out of their cell membrane, using external chemicals such as soil iron oxides as a solid state electron acceptor. In other words, these naturally occurring microbes respire, or "breathe," solid state electron acceptors. By replacing the external electron acceptor with an anode and allowing the electrons to flow to a cathode (where a terminal electron acceptor such as oxygen is present), a soil microbial fuel cell can be constructed. In this system, microbes are simply the redox catalyst, enabling extraction of electrons from soil organic matter and routing these electrons to an external circuit. While wastewater- and sediment-MFCs have been intensively researched for >15 years, soil MFCs have seen comparatively little investigation, especially outside the lab targeting real world applications.

The intensity and duration of energy generation by microorganisms from the soil are affected by soil properties, environmental conditions, and microbial communities. Although framed as the "fuel" for MFCs, soil organic content is not the sole factor impacting power production. Different types of soil result in a wide range of power generating abilities. Dunaj, et al. [3] reported that the peak power output from soil MFCs could be 17 times higher in the less organic-rich yet more microbially active agricultural soil than forest soil. Soil water content needs to reach a certain level for MFCs to produce noticeable power [4]; therefore, precipitation and site irrigation schedules are crucial to maintaining soil MFCs' power output. As temperature affects microbial activities, power production from soil MFCs is positively related to temperature in the range of normal outdoor temperature [5,6]. In addition, the selection and enrichment of electrogenic bacteria on the anodes contribute to the MFC power output, which is dependent not only on the inoculum or the soil microbial community to start with but also on the above-mentioned soil properties and environmental factors. Microbial communities on anode surfaces in soil MFCs develop different compositions compared to the original soil. It has been shown that high power-producing MFC anode microbial communities are less diverse, and exoelectrogenic bacteria such as *Geobacter* and *Clostridium* are present in large amounts [7].

The application of soil-based MFCs for power harvesting faces unique challenges compared to aqueous MFCs, due to the nature of soil as the MFC substrate and the microscale spatial variability of surrounding environments. MFC voltage output deviates from the theoretical values mainly through ohmic loss, concentration loss (mass transport loss), and activation loss. Mass transport in a porous medium like soil is much slower than that in an aqueous MFC, since it relies heavily on the pore water movement and the interactions with the medium itself. The separation of oxic/anaerobic conditions for the cathode and anode is crucial to the occurrence of bioelectrochemical reactions in an MFC. Oxygen should be accessible at the cathode to accept the electrons, while the exoelectrogenic heterotrophic bacteria require anaerobic conditions to degrade organics around the anode. Therefore, there is a trade-off between the internal resistance, which is positively related to the cathode-anode distance, and anaerobic conditions that are required at the anode, which generally increase with soil depth [8]. Unlike aqueous MFCs, which have largely been proposed for integration in relatively well-controlled wastewater treatment bioprocesses, soil MFCs are expected to be embedded in water-soil systems where the controllability over environmental factors like temperature, pH, dissolved oxygen, and precipitation are very limited. Since

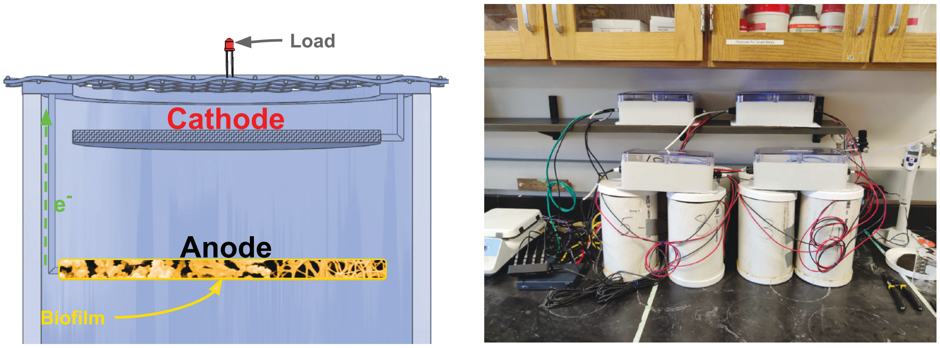

FIGURE 2. (a) Diagram of a microbial fuel cell with carbon felt electrodes. Initially there is no potential, but as a microbial biofilm forms, power output rises. (b) A photograph of cells in the laboratory. After 60 days, the biofilm is able to provide a consistent output of 15-25 μW.

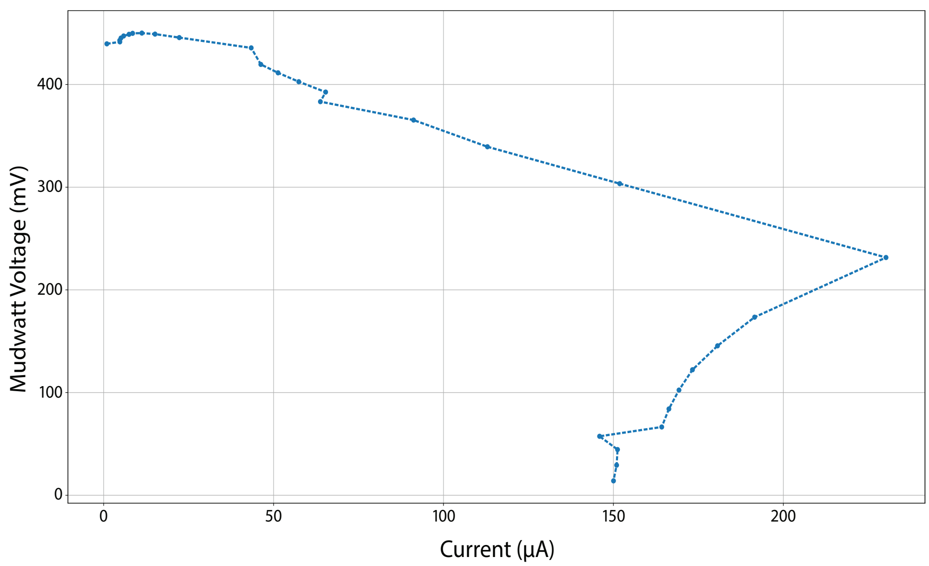

FIGURE 3. Voltage vs. current sweep of a year-old cell. Normally, current increases as voltage decreases, but after an inflection point, both decrease in tandem.

the environmental conditions are always dynamic and hardly the optimum for soil MFCs, the power output is inherently low and highly unstable. Better assessment of suitable application scenarios and adaptation of the soil MFCs based on site-to-site differences are necessary for maximizing the power output and improving the power stability.

While improving MFC power output stability and intensity could alleviate power harvesting challenges to some extent, adapting the power harvesting systems to accommodate the inherently limited instantaneous power is necessary. In addition, special considerations are needed for the energy harvesting systems to work with living microbial communities. For example, the harvesting system should endure relatively long "sleep" periods to allow the anodic microbial communities to acclimate and colonize during the incubation phase.

What influences MFC power output?

- soil temperature and moisture
- presence of organic matter
- microbial community (i.e., location)
- oxygen availability
- soil depth
- cell size, geometry, and materials

HARVESTING FROM MFCS

Capturing bacterial power is challenging due to the limited instantaneous power and the environmental- and time-varying output power. We began exploring energy harvesting potential with a reproducible "benchtop" MFC. Our initial design is similar to the Mudwatt, a commercially sold children's science kit [9]. In addition to the benchtop MFCs, we also designed variants adapted to make transferring the cells to an outdoor deployment easier. All cells, whether designed for indoor or outdoor observation, were incubated indoors where we could create an environment optimal for the microbes to facilitate strong biofilm development.

So how much energy can these microbes generate? Figure 3 measures the output power available from the cell across varying simple resistor loads. While the instantaneous power is low, it is stable, which allows an energy scavenging system to integrate power over time. Modern harvester ICs such as the LTC 3108 can cold-start from as low as 20 mV. Mature soil MFCs actually have significantly higher potential, so we choose the ADP 5091 (cold-start 380 mV; minimum steady-state input 80 mV) for its better efficiency.

Remarkably, our initial experiments with energy harvesting ICs find that they extract less power from the soil MFC than a simple, static, resistor load. We use a RocketLogger [10] to measure the voltage and current coming off of our benchtop MFC. As a baseline, attaching a 2.2 kΩ resistor causes the cell to stabilize at 100 μW. Figure 4 shows the behavior of the ADP5091 when it tries to harvest. During the on-periods, the effective impedance of the harvester is very low, which causes the MFC output power to fade over time. Even when trying to hold 95% open circuit voltage, the maximum MPPT set point of the ADP5091, the harvester drains the MFC to non-operation. Readers interested in more detail on the behavior of this harvester are referred to our LP-IoT '21 paper [11]. We see this, then, as an exciting research direction, namely, how to design harvesters capable of better extracting power from limited, living energy sources.

Figure 3 shows the relationship between voltage and current from a cell across varying simple resistor loads. Normally, as the resistance decreases, current increases. However, here we see that after a certain inflection point both current and voltage decrease. Additional tests indicate that after this inflection point, it is not possible to "return" to the higher power production of the cell by increasing the resistance. The cells need to be disconnected for some time before their power production recovers. We believe that this cell behavior is the reason that current commercial-off-the-shelf energy harvesters are not able to draw more power.

In addition to new harvesters, we can also look at cell design and networks of cells. We can make cells larger, but scaling up often results in decreased current density when normalized by electrode area [12,13]. Preliminary experiments with a parallel array of benchtop MFCs show superlinear improvement in power dissipated across a static load — nearly 700 µW across a 2.2 kΩ load with four cells in parallel (versus 100 µW from one cell). Naively arranging the cells in series, however, results in markedly sublinear performance, with four cells in series producing a lower output voltage than one cell alone. This is likely due to the voltage reversal problem in MFCs, where internal resistance spikes over time when cells are stacked [14,15]. Prior work has shown that dynamic switching of configuration can mitigate this [16], though it remains to be seen whether this will work in soil-based designs and how to manage cold-start of a design with switches between cells.

Looking forward, moving from the lab to the field will present both challenges and opportunities. One major question is isolation between cells: can cells in a common plot of soil actually be isolated for series or parallel connection? How far apart must they be, in varying moisture conditions, for a network of MFCs to operate as electrically desired? One major opportunity is in additional support structures. We can ameliorate cold starts with eco-conscious, non-renewable sources—a small zinc bar will act as an Earth battery, which can be used as a voltage reference. This emergency reserve can leverage passive corrosion protection system design principles to ensure a lifetime measured in decades.

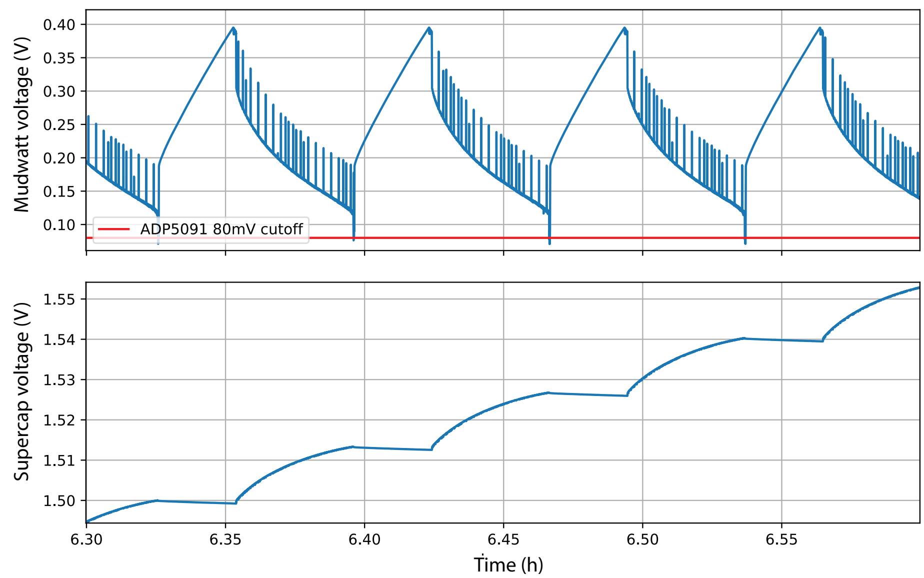

FIGURE 4. Detail view of harvester cycles: At 380 mV, the cold-start circuitry of the harvester activates, and the system begins charging. Every 16s the MPPT algorithm detaches the harvester for 256 ms to measure the open-circuit voltage, accounting for the voltage spikes during harvesting. When the input falls below 80 mV (red line in graph), the harvester shuts off. With no load, the cell recovers until it reaches 380 mV and the cycle restarts.

Takeaway: State-of-the-art Energy Harvesting ICs are incompatible with the unique bio-electronic actions of an MFC, and perform worse than ultra-simple harvesting approaches.

BUILDING SYSTEMS ON MFCS

With an energy source that is as fickle, dynamic, and (un)predictable as the weather, tiny embedded computing systems have to automatically adapt computation, sensing, and communication tasks to make the best use of this oddly predictable, but confounding, energy source. Looking at data from a field deployment of two MFCs, we see correlations between the cell's power output and environmental conditions like the temperature and soil moisture. Despite months of observation, we are still sometimes surprised by what the cells "decide" to do. How can we learn to work with this quasi-behavior, and possibly even leverage it?

This medium-term stable energy income, and medium-term predictable future income, is a new energy income paradigm. It is not reliable in the sense of Jagtap et al. [17]. It is also not intermittent in the sense of RF or photovoltaic harvesting; these sources can have immediate drops in energy income, which imposes stringent requirements for checkpointing that can lead to high overhead in the worst case [18]. Can some of these requirements be relaxed or adapted as the system is now more predictable? Strong correlation between wetness and temperature mean that energy subsystems can be proactive and plan operation rather than reactive to instantaneously obtained (or not) energy.

Soil MFCs exhibit massive dynamic range, easily several orders of magnitude in real-world conditions. This is not necessarily unique to MFCs, as even solar panels see extremes in energy generation (dusk vs midday), however, MFCs are products of a complex environment, not just a simple indicator like sunlight. Building the capability to understand the environmental context, and trigger the task that is most energy-efficient, is an open and hard problem. We imagine programs scaling from very simple tasks (such as sampling a sensor and storing it to memory), to taking a picture, classifying plant health from the image, and transmitting the results. Wide dynamic range requires careful circuit, architecture, and program design. We further imagine variance over time, with the possibility of seasonal applications. MFC-powered sensors in agricultural settings may literally hibernate over the winter. What is the analog to hyperphagia for a sensor that wishes periodic winter activation, and what will hold and mete out its power reserves?

Finally, there is the critical question of how users and applications will interface with these systems. Decades of struggles with memory management have shown that manual administration of resources is very hard to get right, and recent work shows that managing energy may yet be harder still [19]. Prior work has explored event and task-based paradigms for intermittent systems with reasonably consistent energy income [20], but it is not yet clear what the

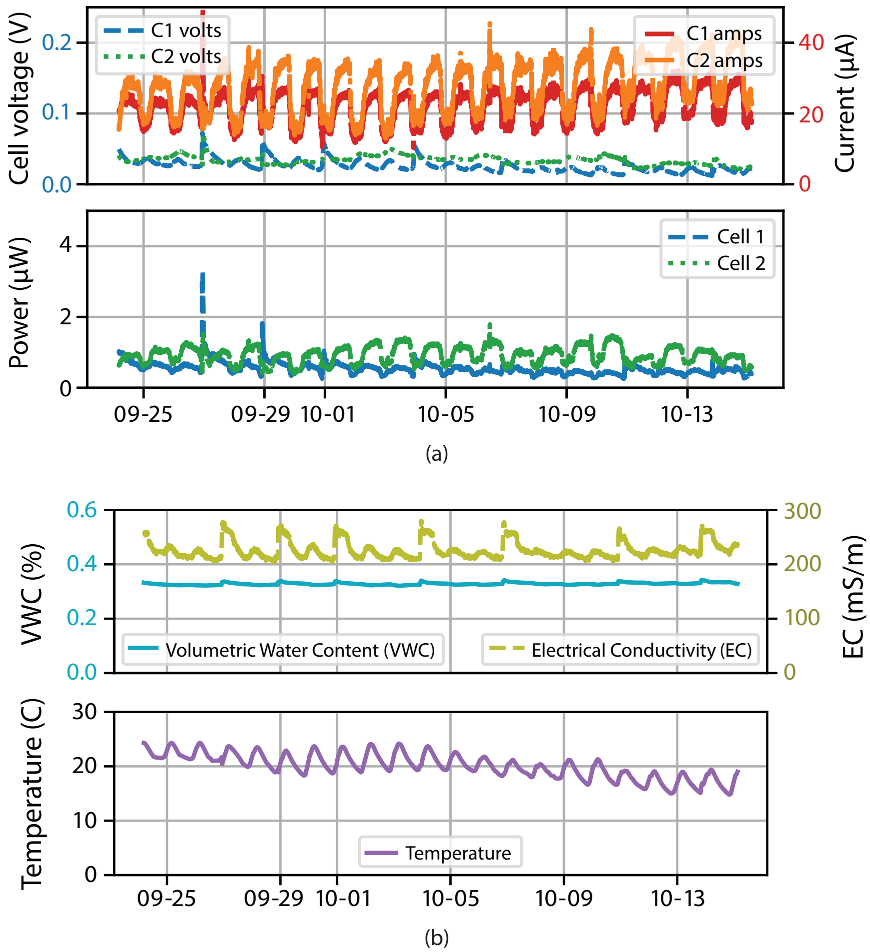

FIGURE 5. (a) Power output of two MFCs deployed on a Stanford, CA, farm field. The sinusoidal pattern corresponds to temperature changes in soil due to sunrise and sunset. The larger spikes in power output are caused by drip irrigation, which runs three times a week. (b) Data from a TEROS-12 soil moisture, electrical conductivity and temperature sensor installed between the two MFCs.

best mechanism is to expose the wide range of operational capability of soil MFCs to software developers.

Takeaway: MFCs present a novel opportunity to harness low but steady amounts of power, but current embedded system practices cannot fully leverage the potential of microbial power.

THE OTHER HALF OF INFRASTRUCTURE

Designing an embedded compute platform that can operate on power harvested by MFCs is essential, but to truly have a soil-powered sensor network we must also consider communication. Our farm deployment demonstrates that it is possible for a single MFC to consistently generate 0.5-2 µW of power.[1] However, even low-power radios like LoRa consume significantly more power while transmitting – 25-125 mW [21]. Fortunately backscatter communication needs as little as a nanowatt [22]. Challenges remain in powering the sensors themselves. Traditional sensors are usually designed to operate between 3-5 V and are often not designed to be especially low-power. However, new sensing technologies, like backscatter-based soil moisture sensing [23], can leverage the backscatter channel to make high-accuracy measurements. This brings a microbe-powered soil moisture sensor network within the realm of possibility.

REMARKABLY, OUR INITIAL EXPERIMENTS WITH ENERGY HARVESTING ICS FIND THAT THEY EXTRACT LESS POWER FROM THE SOIL MFC THAN A SIMPLE, STATIC, RESISTOR LOAD

The extremely low power consumption of backscatter communication comes with a trade-off, however: limited range. Typically backscatter readers need to be within 1-10 m of the tag. To reap the advantages of backscatter communication, we envision leveraging the growing trends of autonomous farming. Drones and agricultural robots have seen rapid adoption in the past few years for applications like aerial imagery, and automated harvesting and sowing [24,25,26,27,28]. These same technologies can be used to collect sensor readings by bringing the backscatter reader close to the sensor tag, similar to how mobile RFID readers can be used in warehouses to track assets [29].

In contrast to traditional sensor networks, where sensor nodes are equipped with longer-range active radios that send the data to a centralized location like a farmhouse, a mobile reader system flips this model and precludes the need to build out extensive dedicated infrastructure.

Although we know that backscatter-based communication is feasible, that doesn't mean that more traditional communication is impossible. More work is needed to fully understand how much power can be harvested from fuel cells. It is possible that improved design and techniques like

[1] As we discussed earlier in "Harvesting from MFCs," it remains to be seen how much of the generated power we can actually harvest given the limitations of off-the-shelf harvesting chips.

stacking multiple cells in series or parallel can boost the amount of available power. While it is unlikely that MFC-powered communication will ever support realtime or high-bandwidth transmissions, we know agricultural sensor networks are typically low-bandwidth and latency tolerant. Depending on the workload, it may someday be possible for more advanced soil MFC deployments to support transmission of a few packets per day using traditional sensor network communications like LoRa.

MOVING FORWARD

Practical, large-scale, decades-long deployment of soil powered sensing systems is on the horizon. Advances in microbial fuel cells and low-power electronics are hitting an inflection point at nearly the same time; now all that is needed is work that bridges the remaining gap. We view this article as a blueprint for our community to participate in constructing that bridge: we introduce the basics of MFCs to the mobile computing community, present preliminary work, and also outline the future work needed. The potential to leverage a small but steady source of renewable power is enticing, and many interesting questions remain in the space of MFC design, harvesting techniques, embedded systems paradigms and communication techniques. As we learn more about what makes soil-based MFCs tick, it will improve our ability to predict how cells will behave over time. This, we hope, will lead to insights that make soil-powered sensor networks practical. These systems come at a crucial time for computing and the world, as we consider the effects of computing on climate change, and possible mitigations and resilience capabilities that could be enabled by emerging computing platforms. MFCs, combined with emerging work on bio-degradable computing and sensing, offer a promising mechanism for large-scale, ecologically friendly, long-term monitoring of the soil environment. ■

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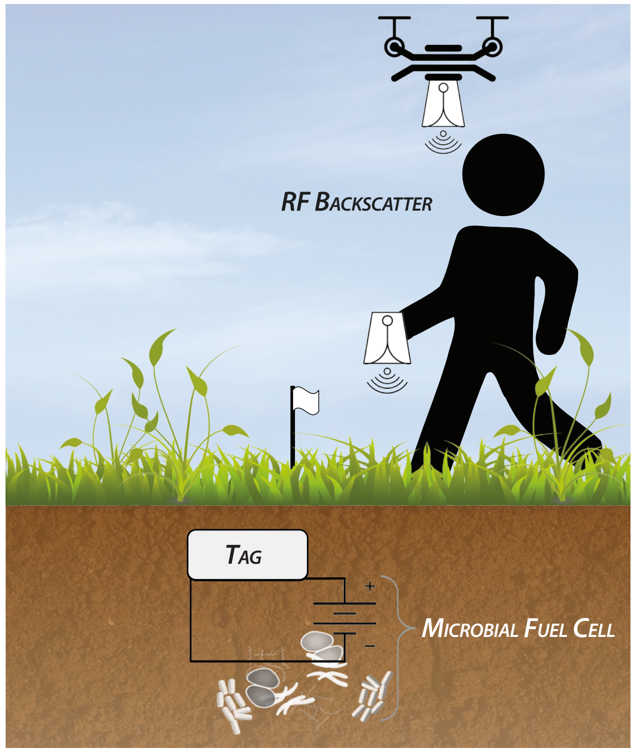

FIGURE 6. One possible approach to leveraging MFCs is powering backscatter sensing systems.

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George Wells is an associate professor in the Department of Civil & Environmental Engineering at Northwestern University. He works at the interface of microbial ecology and environmental biotechnology, with the goal of developing novel engineered microbial systems to harvest energy, clean water, enable sustainable food production, recover resources from societal waste streams, and mitigate greenhouse gas emissions. Core research interests include biofilms and biofilm processes, microbial electrochemical systems, microbial community genomics, and microbial nutrient cycling.

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